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ORIGINAL RESEARCH PAPER

EFFECT OF PRE-TREATMENT AND AIR TEMPERATURE ON DRYING KINETICS AND QUALITY OF JERUSALEM ARTICHOKE

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Abstract: The effect of pre-treatment and air temperature on the drying kinetics and some quality criteria of Jerusalem artichoke were investigated. The pre-treated and untreated of Jerusalem artichoke slices were dried in a cabinet dryer at temperatures of 60, 70 and 80 °C. It was found that air temperature and pre-treatment had more significant effects on drying kinetics, color and rehydration ratio. The experimental data were adjusted to seven thin-layer drying models in the representation of vegetable and fruit drying. The Midilli & Kucuk model was best fitted to measurements. The effective moisture diffusivity at each temperature was determined by Fick's second law of diffusion, in which their value varied from 5.49×10^{-10} to 1.90×10^{-9} $m^2\cdot s^{-1}$ over the mentioned temperature range. The values of the activation energy of moisture diffusion were 50.74 and 40.21 $kJ\cdot mol^{-1}$ for citric acid and control samples, respectively.

Keywords: *activation energy, drying, effective moisture diffusivity, Jerusalem artichoke, mathematical modelling*

INTRODUCTION

Jerusalem artichoke (*Helianthus tuberosus* L.) is raised irrespective of climate conditions, and its tubers can be produced in world-wide [1]. It produces fleshy underground tubers rich in inulin and related carbohydrates [2]. Artichoke tubers contain useful compounds for use as raw materials for foods. Jerusalem artichoke flour includes high complex carbohydrate like inulin. It contains carbohydrate (up to 82 %), proteins (up to 7 %), fat (0.3 - 0.7 %), pectin (10 %), fiber (7 %), organic acids, macro- and trace elements [3, 4]. It could be considered as a good source of vitamins (vitamin B complex, vitamin C and β-carotene) and minerals (calcium, iron, selenium, potassium, phosphorus) [5]. There are numerous factor changing microbiological, enzymatic, biochemical properties of the food material during long term storage. As a result of these changes, quality of food products may be decreased. Natural or artificial drying products are widely used to inhibit microbial growth and enzymatic activity. Therefore, the Jerusalem artichokes should be dried for storage, handling and processing.

Drying is one of the main methods in food preservation to provide high shelf-life, lighter weight for transportation, and less space needed for storage. There are many types of drying methods in literature. Despite the development of several new drying techniques, most vegetables are still dried with hot air because this drying method is still the simplest and most economical. Numerous data has been reported in the literature on the drying properties of different products such as cocoyam [6], yam [7], ginger [8], and Jerusalem artichoke [9 – 11]. In some studies, the effect of pre-treatment on the drying rate of agricultural products and drying time has been investigated by various authors. In these studies, sodium and potassium hydroxide, potassium carbonate, potassium metabisulfite, ethyl and methyl ester emulsions, citric and ascorbic and were mostly used as pre-treatment solutions [12 – 19]. Pre-treatments can increase quality of the products by preventing loss of color by inactivating enzymes in addition to increase drying rate by relaxing tissue structure [12]. Although there are a few studies in the literature on the drying of Jerusalem artichoke, no work has been found detailing the influence of pre-treated with citric acid solution on drying characteristics of Jerusalem artichoke. The main objectives of this study were to investigate the effect of temperature on drying and color and rehydration characteristics, fit the experimental data to seven thin-layer drying models, and compute effective moisture diffusivity and activation energy of Jerusalem artichoke.

MATERIALS AND METHODS

Materials

Fresh Jerusalem artichoke tubers were purchased from a local market in Istanbul and stored at 4 °C. The tubers were washed with tap water and hand-peeled with a knife, and then cut sliced into 5 mm and 10 mm thickness (d) using a lab-scale slicer. The free water on the surface of samples was removed with an absorbent filler paper. The samples were divided two groups: (1) no pre-treatment (Control) and (2) soaking in 1 % (w/v) citric acid solution (Citric acid). The initial moisture content of Jerusalem artichoke was determined by using an oven at 105 °C for 24 h. Triplicate samples were used for the determination of moisture content and the average values were reported as 3.1597 kg water·kg^{-1} dry matter (d.b.).

Experimental set up

The tubers were dried in a cabinet dryer (APV & PASILAC Limited of Carlisle, Cumbria, UK) which was described previously by Doymaz [13]. The dryer was started about 30 min before drying experiments to achieve steady-state conditions. The drying experiments were conducted at 60, 70 and 80 °C air temperatures and constant air velocity of 2 m·s^{-1}. Air velocity was measured with a Testo 440 vane probe anemometer (Lutron, AM-4201, Taiwan). Air flow was horizontal to drying surface of the samples. Approximately 35 g of sample was put into the dryer after weighing. Moisture loss was recorded at 15 min intervals during drying. A digital balance (Mettler-Toledo AG, Grefensee, Switzerland, model BB3000) with 0.1 g accuracy was employed in recording the sample weight. Drying was continued until the sample weight attained a constant value. The drying process was continued until the moisture content remaining in the sample was about 0.10 ± 0.01 kg water·kg^{-1} dry matter (d.b.). The dried product was cooled and packaged in low-density polyethylene bags and then heat-sealed and stored in incubators at ambient temperature. The experiments were run in triplicate and the drying curves were plotted using the average values of the moisture content.

Mathematical modelling

Seven semi-theoretical models (listed in Table 1) were selected to describe the drying behavior of the samples.

Table 1. *Mathematical models applied to the drying curves*

Model name	Model	Reference
Lewis	$MR = exp(-kt)$	[20]
Henderson & Pabis	$MR = a\,exp(-kt)$	[21]
Logarithmic	$MR = a\,exp(-kt) + c$	[6]
Midilli & Kucuk	$MR = a\exp(-kt^n) + bt$	[22]
Parabolic	$MR = a + bt + ct^2$	[23]
Wang & Singh	$MR = 1 + at + bt^2$	[24]
Weibull	$MR = exp\left(-\left(\frac{t}{b}\right)^a\right)$	[25]

a, b, c, k, n - empirical constants and coefficients in the drying models

The moisture content (*M*) and moisture ratio (*MR*) of Jerusalem artichokes were calculated using the following equations:

$$M = \frac{W_i - W_d}{W_d} \tag{1}$$

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{2}$$

where: M is the moisture content (kg water·kg^{-1} dry matter), W_i is the weight of sample (kg), and W_d is the dry matter content of sample (kg). M_0, M_e and M_t are the initial moisture content, the equilibrium moisture content, the moisture content at t (kg water·kg^{-1} dry matter), respectively. As the M_e is very small compared to M_0 and M_t values, the M_e can be neglected and MR can be expressed as M_t/M_0 [7, 26].

The drying rate (DR) of Jerusalem artichoke slices at a particular time period was calculated as follows:

$$DR = \frac{M_{t_1} - M_{t_2}}{t_2 - t_1} \tag{3}$$

where t_1 and t_2 are drying times (min); and M_{t_1} and M_{t_2} are the moisture contents (d.b.) at times t_1 and t_2, respectively.

Statistical analysis

Experimental data were analyzed using the Statistica 8.0.550 (StatSoft Inc., USA) software package. The parameters of the models were estimated using a non-linear regression procedure based on the Levenberg-Marquardt algorithm. The goodness of fit for each model was evaluated based on the statistical parameters such as coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error ($RMSE$) calculated as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2}{\sum_{i=1}^{N}\left(\overline{MR}_{pre} - MR_{\exp,i}\right)^2} \tag{4}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - z} \tag{5}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2\right]^{1/2} \tag{6}$$

where $MR_{exp,i}$ and $MR_{pre,i}$ are the experimental and predicted dimensionless moisture ratios, respectively; N is the number of observations; z is the number of constants. A higher R^2 value and lower χ^2 and $RMSE$ values indicate a better fit [6, 19].

Calculation of effective moisture diffusivity

Fick's second law of diffusion equation was used to fit the experimental drying data for the determination of effective moisture diffusivity coefficients:

$$\frac{\partial M}{\partial t} = D_{eff}\frac{\partial^2 M}{\partial x^2} \tag{7}$$

where M is the moisture content (kg water·kg^{-1} dry matter), t is the drying time (s), and D_{eff} is the effective moisture diffusivity (m^2·s^{-1}). The solution of diffusion eqn. (7) for slab geometry is solved by Crank [27] and supposed uniform initial moisture distribution, negligible external resistance, constant temperature and diffusivity, and negligible shrinkage:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2}\right) \tag{8}$$

where L is the half thickness of the slab (m), and n is the positive integer. Equation (8) can be further simplified to only the first term of the series and expressed in a logarithmic form for long drying periods:

$$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{4L^2}\right) \tag{9}$$

The effective moisture diffusivity was calculated from the slope *(K)* of a straight line, plotting experimental drying data in terms of *ln (MR)* versus *time* according to eqn. (9).

$$K = \frac{\pi^2 D_{eff}}{4L^2} \tag{10}$$

Estimation of activation energy

The relationship between effective moisture diffusivity and air temperature is assumed to be an Arrhenius-type equation [28]:

$$D_{eff} = D_0\, exp\left(-\frac{E_a}{R(T+273.15)}\right) \tag{11}$$

Here D_0 is the pre-exponential factor (m^2·s^{-1}), E_a is the activation energy (kJ·mol^{-1}), R is the universal gas constant (kJ·mol^{-1}·K^{-1}), and T is temperature (°C).

Color

The product color was measured using a CR-400 model color meter (Chroma Meter-CR-400 from Konica Minolta, Osaka, Japan). The color value was expressed as CIE L^*, a^*, and b^*, where L^* represents lightness, with 0 for black and 100 for white, a^* is from red to green, and b^* is from yellow to blue. Before the test, a standard white tile was used to calibrate the color meter. Measurements were made directly on the surface. Five replicates were performed for each sample.

Rehydration experiments

Dried samples at different power levels were rehydrated in distilled water at 25 °C. About 2.5 ± 0.1 g dried samples were placed in glass beakers containing distilled water in the ratio 1:160 (w/w). At specified time as 300 min, the samples were then removed, blotted with tissue paper to eliminate excess water on the surface, and weighed with an electronic digital balance (Precisa, model XB220A, Precisa Instruments AG, Dietikon, Switzerland) having a sensitivity of 0.001 g. The rehydration ratio (*RR*) was calculated according to eqn. (12):

$$RR = \frac{W - W_1}{W_1} \tag{12}$$

where: W is the weight of sample (kg), and W_1 is the dry matter content of sample (kg).

RESULTS AND DISCUSSION

Analysis of drying curves

The effect of air temperature on drying curves of Jerusalem artichoke slices (d: 5 mm) is shown in Figure 1. As expected, the drying time was shortened greatly with increasing air-drying temperatures. The drying times required to reach the final moisture content of control samples were 255, 120 and 105 min at air temperature of 60, 70 and 80 °C, respectively. The average drying rate of samples increased 2.42 times, respectively, as air-drying temperature increased from 60 to 80 °C.

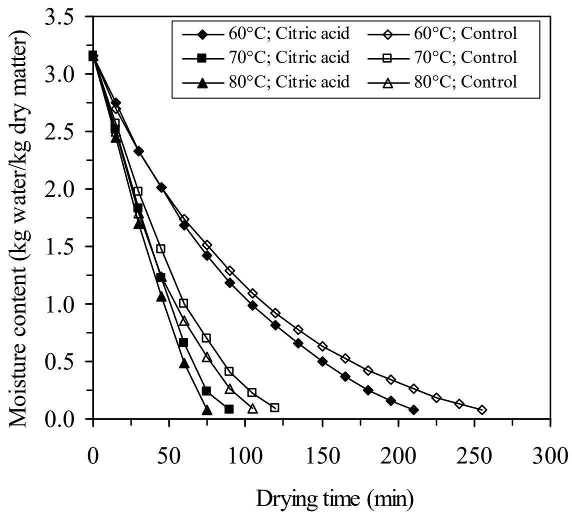

Figure 1. *Variations of moisture content with drying time of pre-treated / untreated Jerusalem artichoke slices (d: 5 mm) at different air temperatures*

Similar trends were observed for citric acid samples**.** The effect of temperature on drying behavior of various vegetables and fruits has been investigated by some researches [7, 14, 15, 17].

Influence of pre-treatment solution

According to the results in Figure 1, pre-treatment is very important parameter that affects the drying time. The samples dipped in citric acid solution before drying process had a shorter drying time compared to control samples. The reach a final water content (0.10 kg water·kg^{-1} dry matter) in control samples, 255 min of drying at 60 °C were needed, respectively, while Jerusalem artichoke slices pre-treated with citric acid solution reached this water content after 210 min. The difference in drying times was close to 21.4 %. These results show that citric acid solution contributed to increase the permeability of the cell membranes of Jerusalem artichoke slices, leading to an increase in water diffusivity. Similar trends were observed at drying temperatures of 70 and 80 °C. The observed pre-treatment characteristics were also reported in previous studies on different agricultural products [15, 16, 19].

Slice thickness

Figure 2 shows the drying curves of control samples at 60 °C for different slice thicknesses. It is clearly evident from these curves that the drying rate was higher at thin slices and the total drying time reduced substantially with the decrease in slice thickness. The drying times of control samples were 255 and 375 min, respectively, in relation to the slice thickness of 5 and 10 mm. The drying time of 5 mm slice thickness samples was shortened by 32 % compared with the drying process realized at 10 mm slice thickness samples. Thinly sliced products dried faster due to the reduced distance the moisture travels and increased surface area exposed for a given volume of the product. The similar observations were found by Ertekin and Yaldiz [29] for drying of eggplant slices, Khazaei *et al.* [30] for drying of tomato slices, and Falade and Solademi [31] for drying of sweet potato slices.

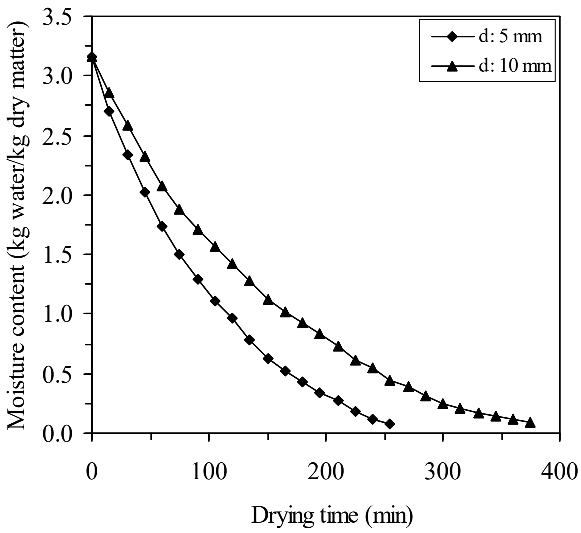

Figure 2. *Effect of slice-thickness on drying time of Jerusalem artichoke slices at 60 °C*

Drying rate

The drying rate curves of Jerusalem artichoke slices (d: 5 mm) are shown in Figure 3. It is clear that the drying rate decreases continuously with moisture content. The drying rates were higher in the beginning of the process, and then decreased with a decrease in moisture content of the samples. The reason for the decrease in drying rate might be due to a reduction in the porosity of samples caused by shrinkage with advancement, which increased the resistance to movement of water leading to further fall in drying rates [32]. This observation is in agreement with previous studies on drying of foodstuffs [33, 34]. Jerusalem artichoke did not exhibit a constant drying rate period and all the drying operations are seen to occur in the falling drying rate period. These results are in good agreement with those in earlier studies of various vegetables [7, 17, 25, 35].

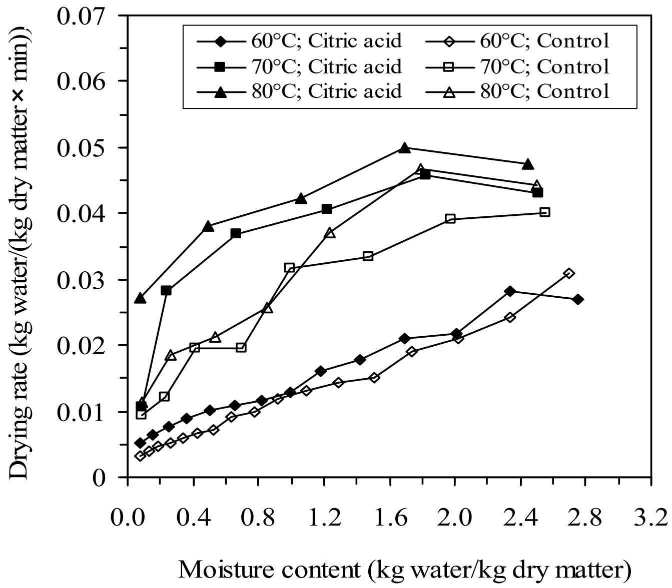

Figure 3. *Variations of drying rate as a function of moisture content of pre-treated / untreated Jerusalem artichoke slices (d: 5 mm) at different air temperatures*

Evaluation of models

The moisture content data obtained from the drying experiments were fitted seven thin-layer drying models identified in Table 1. The best model selected is based on the highest R^2 and the lowest χ^2 and *RMSE* values. Results of the statistical computing are shown in Table 2. The R^2 values for all models were above 0.95. Among the seven thin-layer drying models tested, Midilli & Kucuk model obtained the highest R^2 values and the lowest $\chi^2$and *RMSE* values in all the drying conditions studied. It is clear that, the R^2, χ^2 and *RMSE* values of this model were changed between 0.9988-0.9999, 0.000011-0.000019 and 0.006148-0.013343, respectively. Figure 4 compares experimental data with those predicted with the Midilli & Kucuk model for Jerusalem artichoke slices. As shown, the predicted moisture ratios are generally banded near to a 45° straight line, indicating the capability of the model to describe the drying behavior of the samples appropriately. The same results have been reported in the literature in term of the Midilli & Kucuk model capability to describe the drying behavior of different fruits and vegetables [8, 10, 26].

***Table 2.** Statistical results obtained from the selected models*

Code	T [°C]	Model name	R^2	χ^2	*RMSE*
Citric acid	60	Lewis	0.9871	0.001238	0.111011
		Henderson & Pabis	0.9896	0.001073	0.098220
		Logarithmic	0.9998	0.000014	0.011385
		Midilli & Kucuk	0.9999	0.000013	0.010725
		Parabolic	0.9985	0.000158	0.040394
		Wang & Singh	0.9981	0.000192	0.043389
		Weibull	0.9966	0.000347	0.054747
	70	Lewis	0.9558	0.006023	0.165523
		Henderson & Pabis	0.9619	0.006221	0.167292
		Logarithmic	0.9958	0.000073	0.019936
		Midilli & Kucuk	0.9988	0.000019	0.009757
		Parabolic	0.9972	0.000049	0.016859
		Wang & Singh	0.9967	0.000057	0.016536
		Weibull	0.9960	0.000069	0.017815
	80	Lewis	0.9527	0.006545	0.149222
		Henderson & Pabis	0.9582	0.007237	0.155572
		Logarithmic	0.9990	0.000221	0.022362
		Midilli & Kucuk	0.9999	0.000033	0.006148
		Parabolic	0.9993	0.000158	0.018408
		Wang & Singh	0.9991	0.000141	0.017795
		Weibull	0.9940	0.001036	0.047938
Control	60	Lewis	0.9947	0.000464	0.073267
		Henderson & Pabis	09952	0.000448	0.072282
		Logarithmic	0.9998	0.000012	0.010986
		Midilli & Kucuk	0.9999	0.000011	0.010337
		Parabolic	0.9967	0.000321	0.056342
		Wang & Singh	0.9939	0.000564	0.080032
		Weibull	0.9975	0.000228	0.049912
	70	Lewis	0.9778	0.002600	0.120480
		Henderson & Pabis	0.9819	0.002425	0.116301
		Logarithmic	0.9983	0.000252	0.035302
		Midilli & Kucuk	0.9997	0.000045	0.012936
		Parabolic	0.9996	0.000059	0.015350
		Wang & Singh	0.9995	0.000060	0.014955
		Weibull	0.9981	0.000248	0.034070
	80	Lewis	0.9800	0.002425	0.104002
		Henderson & Pabis	0.9834	0.002345	0.104722
		Logarithmic	0.9987	0.000217	0.025496
		Midilli & Kucuk	0.9997	0.000054	0.013343
		Parabolic	0.9992	0.000135	0.021846
		Wang & Singh	0.9991	0.000117	0.020029
		Weibull	0.9980	0.000278	0.032608

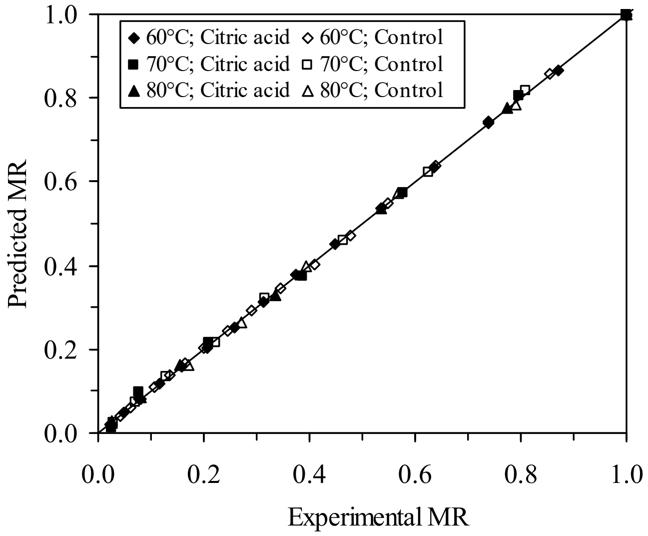

Figure 4. *Experimental vs. predicted moisture ratios using Midilli & Kucuk model for Jerusalem artichoke slices (d: 5 mm)*

Effective moisture diffusivity

By plotting ln(MR) against drying time and using the slope methods the effective moisture diffusivity of the samples was calculated under different drying conditions. The values of effective diffusivity (D_{eff}) were calculated using eqn. (10) and are shown in Figure 5.

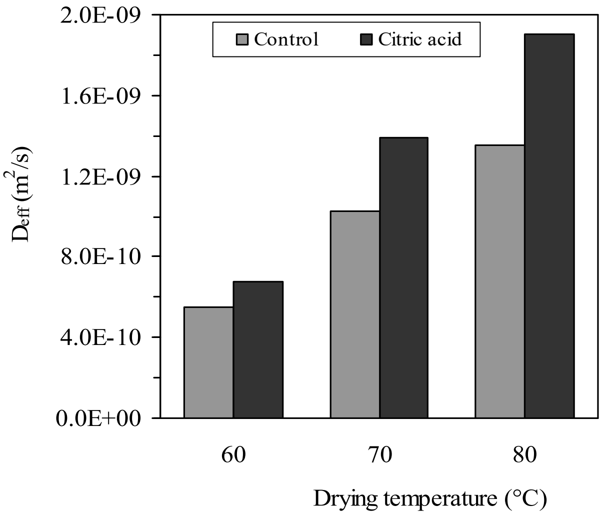

Figure 5. *Variation of effective moisture diffusivity with drying temperature for Jerusalem artichoke slices (d: 5 mm)*

The D_{eff} values of Jerusalem artichoke slices in the drying at 60-80 °C varied between 5.49×10^{-10} and 1.90×10^{-9} $m^2\cdot s^{-1}$. It can be seen that D_{eff} values increased greatly with increasing air temperature. Drying at 80 °C has the highest value of D_{eff} and the lowest value was obtained for 60 °C. The values of D_{eff} from this study lie within in general range 10^{-12} to 10^{-8} $m^2 \cdot s^{-1}$ for drying of food materials [36]. The obtained moisture diffusivity values for the Jerusalem artichoke slices agree well with the values reported in the literature. Poorfallah *et al.* [9] reported the diffusivity values to be in the range of 5.13×10^{-9} - 1.20×10^{-8} $m^2 \cdot s^{-1}$ for dried at temperatures of 60 - 80 °C. Porniammongkol *et al.* [10] reported effective moisture diffusion coefficient of Jerusalem artichoke slices in the ranges of 3.63×10^{-9} to 4.06×10^{-9} $m^2 \cdot s^{-1}$ for dried at 60 °C. Khuenpet *et al.* [37] dried Jerusalem artichoke slices at temperatures of 55, 65 and 75 °C and reported the effective moisture diffusivity to be in the range of 1.56×10^{-10} to 3.14×10^{-10} $m^2 \cdot s^{-1}$. The differences between the results could be due to the composition structure, shape and initial moisture content of material, as well as the drying temperature, pre-treatments, and drying equipment.

Activation energy

A plot of ln (D_{eff}) as a function of 1 / (T + 273.15) is produced a straight line with a slope equal to ($-E_a/R$), so E_a can be easily estimated (Figure 6).

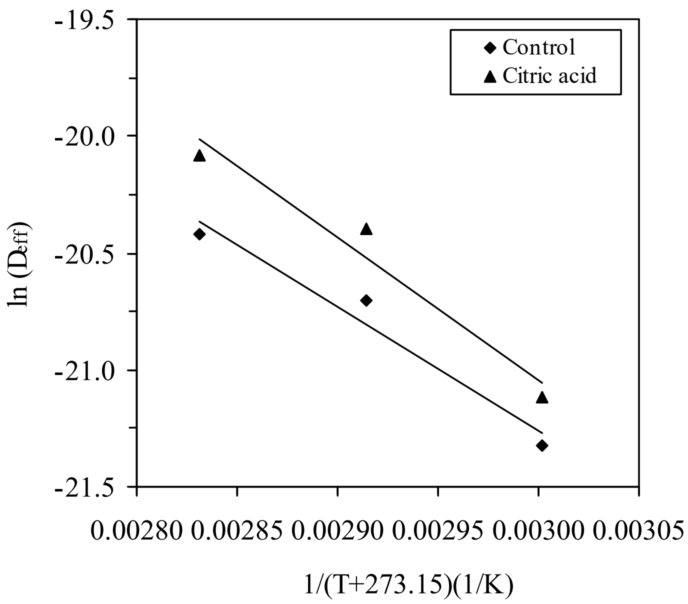

Figure 6. *Arrhenius-type relationship between effective moisture diffusivity and reciprocal absolute temperature for Jerusalem artichoke slices (d: 5 mm)*

Equations (13) and (14) show the effect of temperature on D_{eff} of the pre-treated and the control samples with following coefficients:
Citric acid:

$$D_{eff} = 6.491\times10^{-4} \exp\left(-\frac{6103}{T+273.15}\right) \qquad (R^2 : 0.9578) \qquad (13)$$

Control:

$$D_{eff} = 4.943 \times 10^{-3} \exp\left(-\frac{5317.6}{T + 273.15} \right) \qquad (R^2 : 0.9607) \qquad (14)$$

The activation energy values were 50.74 and 40.21 kJ·mol^{-1} for citric acid and control samples, respectively. The values of activation energy lie within the general range of 12.7 - 110 kJ·mol^{-1} for food materials [36]. The activation energy values recorded in the present study to reasonable agreement with the activation energy recorded for drying of Jerusalem artichoke in the literature: 23.37 - 31.93 kJ·mol^{-1} [9], and 28.1 kJ·mol^{-1} [11].

Color evaluation

Color is considered to be one of the most important criteria determining product quality and consumer preference. The color was expressed as the *L**, *a** and *b** values of the CIELAB color system. The color parameters *L**, *a** and *b** have been widely used to describe color changes during thermal processing of products. The color values as *L**, *a** and *b** were significantly affected by the drying temperature and pre-treatments (Figure 7).

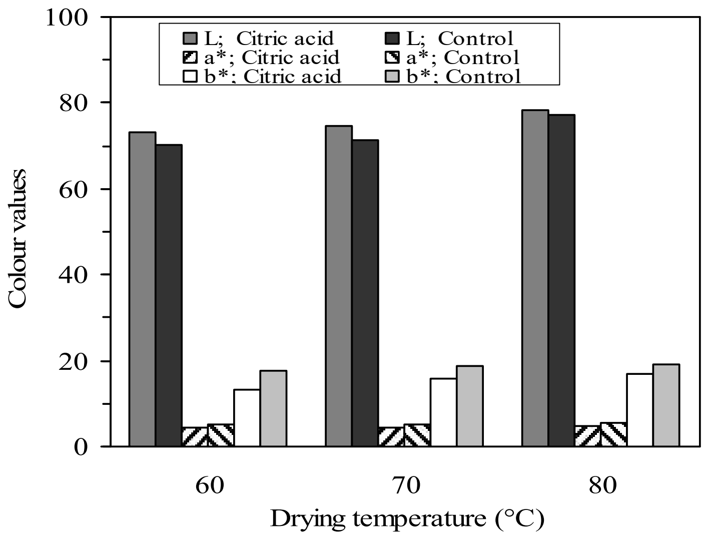

***Figure** 7. Color values of Jerusalem artichoke slices (d: 5 mm) dried at various air-drying temperatures*

The pre-treated artichoke slices with citric acid solution produced higher *L** values than those control ones at whole air temperatures. Moreover, *L** value increased with increase air temperature. The L* values of the dried samples with citric acid solution and control ranged from 73.26 to 78.42, and from 70.09 to 77.17, respectively.

The Hunter *a** value (redness) was higher in control samples than those in pre-treated samples with citric acid solution at all air temperatures. The browning, which was higher in control samples, may be responsible for this. The increase of redness was higher at higher drying temperatures. Therefore, the samples tended toward greater redness values with the progressing drying time. On the other hand, the creation of

brown pigments in the effect of non-enzymatic processes (Maillard reaction) during drying process might play an important role in the production of red color.
Hunter *b** values (yellowness) were higher in control samples than those in pre-treated samples with citric acid solution at all air temperatures. Yellowness showed a slight increase in its value as temperature increased as a result of generation of yellower at high temperature.

Rehydration ratio

Rehydration ratio (RR) is a widely used quality index for dried products. Rehydration values provide information about the changes in physical and chemical properties of a dried sample attributed to drying and treatments preceding dehydration [38]. To investigate the effect of drying conditions on final product quality, the values rehydration ratio of dried Jerusalem artichoke slices were calculated by using eqn. (12) and shown in Figure 8.

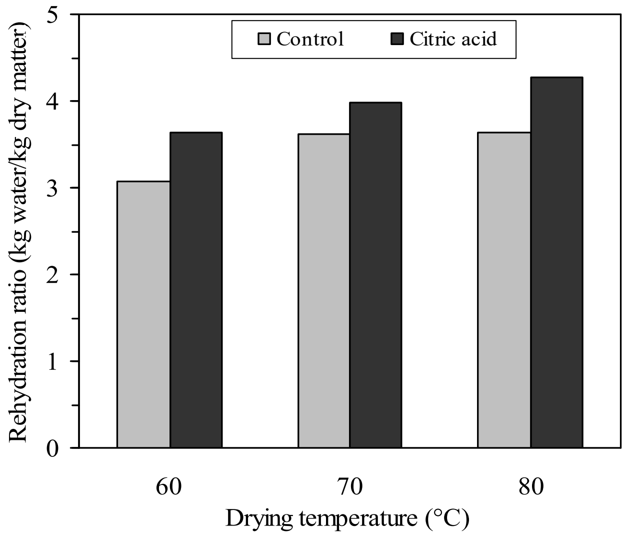

Figure 8. *Effect of pre-treatment and air-drying temperature on rehydration ratio of Jerusalem artichoke slices (d: 5 mm)*

The RR values of dried samples increased with increase air-drying temperature, showing a higher RR of 4.264 kg absorbed water·kg^{-1} dry matter at 80 °C. Furthermore, the RR values of pre-treated with citric acid solution were higher than those control ones at all air temperatures. It can be said that citric acid solution caused the low physical damage in the samples.

CONCLUSIONS

Drying characteristics of Jerusalem artichoke slices were investigated in a cabinet dryer at various temperatures of 60, 70 and 80 °C and constant air velocity of 2 m·s^{-1}. The air temperature and pre-treatment had more significant effects on drying time and quality characteristics such as color and rehydration ratio. The drying process was observed to take place entirely in the falling rate drying period and hence moisture migration to the surface is based on diffusion. Midilli & Kucuk model gave the best representations of drying data under all experimental conditions. The effective moisture diffusivity was found in the range of 5.49×10^{-10} to 1.90×10^{-9} $m^2\cdot s^{-1}$ as the drying temperature increased from 60 to 80 °C. The values of activation energy were determined to be 50.74 and 40.21 $kJ\cdot mol^{-1}$ for citric acid and control samples, respectively.

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